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TECHNICAL NOTE

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DETERMINATION OF NUCLEAR-ROCKET POWER LEVELS FOR UNMANNED MARS VEHICLES STARTING FROM ORBIT ABOUT EARTH

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E-943

CONTENTS

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SUMMARY

For unmanned, one-way trips from an orbit around Earth to an orbit about Mars, nuclear-powered hydrogen-rocket vehicles have greater payload capacities than chemical vehicles for all reactor powers in excess of about 50 megawatts. Use of nuclear-powered vehicles for this mission must await development of chemical boosters capable of placing at least 30,000 pounds (13,600 kg) in an orbit about Earth.

The reactor power of a 33,000-pound (15,000-kg) vehicle must be about 150 megawatts to place a payload of the order of 2000 pounds (900 kg) into orbit about Mars. In a vehicle of this size little payload increase is obtainable by using reactor powers greater than 150 megawatts. The corresponding power for an 81,000-pound vehicle (36,700 kg) is about 400 megawatts, and for a 200,000-pound vehicle, about 1000 megawatts. A hydrogen stagnation temperature of 4000° F (2200° C) in the nozzle appears to be a good compromise between rocket performance and severity of reactor materials problems. In a 33,000-pound vehicle, a temperature of 3500° F (1900° C) is too low for a feasible mission.

It was determined that for a 33,000-pound vehicle a coast time of greater than 200 days is necessary, but the firing date must be close to optimum for a successful mission. Furthermore, in this size vehicle the powerplant weight must not exceed about 7000 pounds (3200 kg). Use of an 81,000-pound vehicle can reduce the coast time to about 145 days. Or, alternatively, it appears feasible to soft-land a weight of about 12,000 pounds on Mars' surface using a vehicle of this weight. For both missions, the firing date must be close to optimum. A month's deviation in firing date decreases the estimated payload weights over 40 percent.

A 200,000-pound (90,700-kg) vehicle powered by a 1000-megawatt reactor could be used either for round trips to Mars or to reduce drastically the coast time of one-way unmanned trips. Meteoroid protection of the hydrogen tanks to the extent of providing a 92-percent probability of no hazardous hits decreases the payload in orbit about Mars by about 1100 pounds (500 kg) for a 30,600-pound (13,880-kg) vehicle.

INTRODUCTION

Use of nuclear power for interplanetary space travel is of great interest because of the high specific power potential of the fission process and high specific impulse obtainable by transferring the fission energy to a propellant of low molecular weight such as hydrogen. The types of nuclear powerplants and hydrogen flow systems for space propulsion can vary over a wide range.

For booster application, however, the many problems arising from the need for tremendously high reactor power may eliminate the feasibility of nuclear-powered boosters in the near future. But when launched from an orbit about Earth, even a low-powered rocket can accomplish interplanetary travel provided that the powered phase is of sufficiently long duration. It would appear, therefore, that the earliest application of nuclear power to space travel might best be made as a nuclear stage boosted into an orbit about Earth by chemical means.

Reference 1 shows that acceptable payloads are possible in unmanned passing shots by Mars, using a low-power (6.7-mw) nuclear last stage. The assumptions used in this reference are quite optimistic. A continuing effort is also being made to study reactors of various materials and geometries. Some of this work is reported in references 1 and 2.

A project was conducted at the NASA Lewis Research Center to study the conditions and nonnuclear aspects of design for nuclear rockets intended for unmanned, one-way trips to Mars. For this project the nuclear stages, assumed to be placed in an orbit about Earth by chemical boosters, have gross weights of 33,000 and 81,000 pounds (15,000 and 36,700 kg), which are typical of the payload capacities of Saturn-class boosters. The primary role of the present report in this program is to define reactor power levels suitable for ambitious unmanned Mars missions. In addition to this primary function, this report presents residual load (vehicle guidance and control equipment + auxiliary power equipment + payload structure + payload container + payload) based on tank and structural weights assumed as percentages of required propellant weight. The residual loads can be used as a starting point in payload estimation for vehicles of various weights if the reader supplies his own tank- and structural-weight assumptions. In developing the overall project, reference 3 uses values of reactor power suggested herein as a basis for making detailed tank designs for two particular vehicles. The project is concluded with reference 4, in which the two vehicles are designed in detail to provide an estimation of payload. The mission of one vehicle is to place a payload in orbit about Mars; the other is to soft-land a payload on the surface of Mars.

Starting from an orbit about the Earth, the flight schedule consists of an outward spiral from Earth, coast in a portion of an elliptic orbit about the Sun, and a decelerating spiral into an orbit about Mars. The nuclear reactor is assumed to be shut down during the coast phase. To provide a basis for detailed designs of vehicles, variations in coast

E-943

time, altitude at Mars, hydrogen temperature in the nozzle, and vehicle weight leaving the orbit about Earth are studied. Several additional factors are also considered, including deviation from optimum firing date, meteoroid protection of the hydrogen tanks, comparison with chemical vehicles, use of a solid-propellant rocket to decelerate into orbit about Mars, and feasibility of making a soft landing on Mars.

An attempt has been made in the present analysis to incorporate the assumptions necessary to yield values of payload at Mars as realistic as possible at this time. The hyperbolic velocities for both the Earth and Mars ends of the trajectory are obtained from three-dimensional calculations in which the orbits of Earth and Mars are neither circular nor coplanar. Properties of the propellant, hydrogen, from reference 5, are for the "equilibrium" case. Weight allowances have been made for structure, tanks (including provision for meteoroid protection), vehicle guidance and control equipment, afterheat cooling of the reactor, and hydrogen trapped in the lines, tank, and so forth.

Wide ranges of variables are presented to aid in selection of the best combinations. Altitude at Mars varies from 206 to 30,000 miles (179 to 26,070 Int. naut. miles). Coast time ranges from 90 to 260 days. The range of reactor powers used is from 10 to 1000 megawatts. Values of 3500°, 4000°, and 4500° F (1900°, 2200°, and 2500° C) are used for nozzle gas temperatures, and nozzle area ratio is assumed to be 30. Stage weights of 33,000, 81,000, and up to 200,000 pounds (90,700 kg) leaving a 352-statute-mile (306-Int.-naut.-mile) circular orbit about Earth are considered. In all the calculations it is assumed that hydrogen enters the reactor core at 260° R (144° K).

ANALYSIS

Flight Schedule

The flight schedule is illustrated in figure 1. The solid trajectory lines indicate power-on phases when leaving the Earth's surface, launching from the orbit about Earth, and decelerating to an orbit about Mars. The dashed lines indicate the power-off times during startup of the nuclear rocket and orientation to the orbital launch point, coast between Earth and Mars, and coast in orbit about Mars.

The launch from the Earth's surface is to be accomplished by means of a large chemical booster that is assumed to place the nuclear rocket into a 352-statute-mile (306-Int.-naut.-mile) circular orbit. The orbital payloads assumed for these large boosters are 33,000 and 81,000 pounds (15,000 and 36,700 kg); and, for comparison in one figure, values up to 200,000 pounds (90,700 kg) were assumed.

After cutoff of the boosters, the nuclear rocket is separated from the booster, and then a short coast may be desired for orbit determination and launch-point maneuvering. Then the nuclear rocket is assumed to be brought up to power without producing any usable thrust or using any hydrogen.

The thrust of the nuclear rocket during launch from orbit is considered to be tangential; that is, in the direction of the velocity vector. Also the thrust is assumed to begin at full power with no allowance for the transient during startup.

When the nuclear reactor is turned off, the thrust is assumed to be immediately reduced to zero. This, of course, will not exactly represent the actual case, because there must be some hydrogen flow through the reactor to maintain reasonable temperatures. The loss of hydrogen for cooling the reactor after shutdown is taken into account only as a propellant loss that produces no usable thrust. Details of propellant pressurization are not considered in this report. Therefore, in cases where pumps might be desirable, neither bleed nor thrust therefrom is taken into account.

Before deceleration into an orbit about Mars begins, it is assumed that the nuclear rocket will be oriented in such a way that the retrothrust will be directed 180° relative to the velocity vector. During deceleration the thrust is considered to be always 180° from the velocity vector until the power-off condition in the orbit about Mars.

The primary mission of the Mars probes studied herein is the orbiting of Mars with a payload heavy enough to provide for research projects such as picture-taking and transmitting facilities. A periares altitude of one-tenth the value of Mars' radius was selected for use in all calculations. The term periares is used herein to denote the lowest point of the orbit about Mars; apoares denotes the highest. It was felt that a closest approach to the planet of about 200 miles (175 Int. naut. miles) could yield sufficient photographic detail and would avoid the additional retrothrust required and the guidance problems of attaining lower periares altitudes. As will be discussed in connection with figure 2, an apoares altitude of 10,000 miles (8690 Int. naut. miles) was chosen. Table I presents the assumptions and constants used in this analysis.

After shutdown of the nuclear reactor at the destination orbit, no propellant was allowed for cooling the reactor. Some type of payload separation mechanism would probably be required in this case, but no weight penalty was assumed for this.

Flight Integration

Many generalized curves relating to mass ratios required for such missions are available, or easily calculable, but the interpolation of the values available led to errors that were significant percentages of the payload. Therefore, all data points used in plotting the curves in this report are based on actual machine integrated flights unless otherwise noted. Symbols are listed in appendix A, and the equations used in making the flight integrations are presented in appendix B.

The vehicles were assumed to be under the influence of only the thrust of the rocket and the gravitational field of an assumed uniform spherical Earth during orbital launch, under the influence of the Sun's gravitational field during coast to Mars, and under the influence of the retrothrust and a uniform Martian gravitational field when approaching the destination orbit at Mars.

All flights away from the orbit about Earth were integrated by steps until the required hyperbolic velocity was attained. Flights into the destination orbit around Mars were accomplished by starting at the periares of the orbit and integrating backward (i.e., filling the propellant tanks) to simulate the inward flight in reverse. Values of initial weights at the beginning of the retrothrust entering the orbit about Mars were plotted as a function of assumed final weights at the destination orbit. These working curves provided the means of determining the final weights at the destination orbit about Mars for the assumed values of thrust, weight, and coast time.

The hyperbolic velocities corresponding to Earth departure and Mars arrival for various coast times and starting dates were obtained from unpublished NASA three-dimensional multiple two-body calculations. These data are within 1 percent of precision n-body computations. Figure 2 presents the variation of the hyperbolic velocities at both Earth and Mars with coast time. The firing date of each point on these curves is that which permits the minimum sum of the two hyperbolic velocities. Figure 2 was used in making all trajectory calculations herein except those in which the effect of varying the firing date is studied. Although figure 2 pertains to only one synodical period, it is representative of constellations of Earth and Mars that would be selected for launching dates of missions considered. The values of figure 2 are slightly conservative compared with the results of five-body calculations in figure 50 of reference 6, which are for launching data in December 1964.

Calculations

Specific impulse. - For any specified reactor geometry, there is an optimum level of nozzle chamber pressure for each value of reactor power. Ideally, this level would be ascertained by a compromise among nozzle cooling and flow conditions, nozzle weight, pump weight (or tank weight for pressurized systems), reactor flow area, pressure-shell weight, and specific impulse. Such a compromise has not been attempted in this report. In the present calculations nozzle chamber pressures that seemed reasonably compatible with the selected values of reactor power were used. Specific impulse was then obtained from the hydrogen-properties tables of reference 5 using these pressures, nozzle chamber stagnation temperature, and nozzle area ratio of 30 for hydrogen in the equilibrium state. The following schedule of power, pressure, and specific impulse was used:

Reactor power, mw	Nozzle chamber stagnation pressure		Specific impulse, sec, at nozzle chamber stagnation temperature of -		
	lb/sq in. abs	kg/sq cm	3500° F (1900° C)	4000° F (2200° C)	4500° F (2500° C)
10	10	0.7	-----	921.9	972
25	22	1.5	-----	894.5	943.5
50	44	3.1	-----	877	925
100	80	5.6	817.5	867.5	915
150	111	7.8	-----	-----	910
200	140	9.8	-----	860	907
500	370	26.0	-----	850	896.5
1000	1000	70.3	795	843.5	889.5

It so happens that, on a plot of specific impulse against nozzle chamber pressure (made for constant nozzle chamber temperature and area ratio), specific impulse decreases sharply with increasing pressure at low values of pressure. At chamber pressures above about 10 pounds per square inch, however, the curve begins to flatten so that specific impulse is relatively insensitive to minor changes in chamber pressure. Therefore, the above values of specific impulse were used with confidence.

For simplicity, it was assumed that hydrogen stagnation temperature in the nozzle remained constant at the value specified at the reactor exit; that is, the nozzle is assumed to be uncooled. For a cooled nozzle it has been estimated that the thrust would decrease by about 1 percent for the conditions used in the present calculations.

Weight-flow rate. - After the hydrogen temperature at the reactor exit was assumed, the weight-flow rate was calculated by dividing the reactor power by the enthalpy rise in the reactor. It was assumed that 95 percent of the fission energy release was available for heating the propellant. The remaining 5 percent of the energy was assumed to be lost by radiation. Hydrogen enthalpy values were obtained from reference 5. In all the calculations hydrogen was assumed to enter the reactor at 260° R (144° K). This temperature was selected on the basis of unpublished reactor temperature and pressure calculations.

Residual load. - The term "residual load" is used as a measure of estimation of payload in orbit about Mars. The residual load y includes vehicle guidance and control equipment, auxiliary power equipment, payload structure, payload container, and payload.

E-943

E-943

The residual load was determined from the change in vehicle weight during each phase of the journey indicated in figure 1 and the nonpayload weights associated with propulsion of the payload to the destination orbit about Mars. First, the weight at the end of Earth orbital launch was determined by stepwise machine integration. From this weight was subtracted the weight of hydrogen allowed for cooling the reactor during the coast phase. The method of determining the weight of hydrogen for afterheat coolant is described in appendix C. The weight at the end of coast was matched with the working curves at the Mars end of the trip (previously mentioned) to give the empty weight $W_{3,b}$.

The weight of hydrogen calculated from the difference between the vehicle weight leaving the orbit around Earth and the empty weight $W_{3,b}$ was increased by 5 percent to allow for hydrogen trapped in the lines, tank, and so forth. Because the size of the tankage (and hence its weight) is dependent upon the hydrogen expenditure, tank weight was assumed to be proportional to total hydrogen weight. For simplicity, insulation and structure were also included to give the ratio $W_{t+i+s}/W_{H_2,tot}$ for the complete stage. The value of this ratio was arbitrarily taken as 0.24 for the figures presented herein except where otherwise noted. The detailed nuclear stage designs reported in reference 4 resulted in values of 0.29 and 0.26 for 45,000- and 81,000-pound stage weights, respectively. It should be pointed out that the weight of structure in this ratio does not include the interstage, which connects the nuclear stage with the chemical booster. This structural element is assumed to be discarded before application of nuclear power in the orbit about Earth. Structural, meteoroid, and insulation details for this type of nuclear stage are reported in reference 3.

Where residual load is shown isolated from powerplant weight, it is assumed that the powerplant weighs 6000 pounds irrespective of reactor power, vehicle gross weight, and so forth. The powerplant weight includes reactor, reactor controls, reactor shield, nozzle, and turbopump system including starting batteries and motors. The weight of the reactor, the heaviest powerplant component, is determined from nuclear considerations. For the range of reactor power considered herein, it was assumed that reactor weight did not vary with power. In reference 4 powerplant weight was estimated to be 6388 and 6778 pounds in 45,000- and 81,000-pound stage weights, respectively.

The residual load y is then calculated by subtracting from the weight leaving the orbit about Earth, the sum of total hydrogen weight, W_{t+i+s}, and powerplant weight.

<u>Meteoroid protection of hydrogen tanks</u>. - The thickness, and hence the weight, of the hydrogen tank depends on the extent of meteoroid protection provided. A schedule of tank weights and the probability of no hazardous hits by meteoroids, taken from reference 3, was used to calculate residual loads for a vehicle of 30,600 pounds (13,880 kg) leaving the orbit about Earth. This particular schedule applies to a design in which a

small tank containing the hydrogen required for power application at Mars and for afterheat cooling is mounted inside the large tank containing propellant required to leave the orbit about Earth. This arrangement yields lighter tank weights than are possible if a single large tank is designed for meteoroid protection for long periods of time. Because of the relatively short duration of the power-on phase at Earth, the outer tank can be designed for high meteoroid protection without too great a weight penalty. A 98-percent probability of no hazardous hits on the outer tank was assumed in the schedule taken from reference 3. The variation in probability of no hazardous hits, therefore, arises from the degree of protection of the inner tank only.

E-943

The tank weights were used to calculate residual loads. In this calculation the weight of insulation plus structure was assumed to be 54 percent of the tank weights given by the schedule. The value of this percentage generally decreases with increasing stage weight.

Comparisons with Chemical Rockets

Entire mission. - Eventual use of a nuclear-powered rocket for any given mission depends upon the extent to which it may be superior to a chemical rocket. In making such a comparison, a specific impulse of 450 seconds was assumed for the chemical rocket in order that its performance might be as optimistic as can reasonably be expected. Impulsive calculations were used for all the chemical vehicles. This procedure introduces some measure of approximation. It is anticipated that hydrogen-oxygen systems of the future will develop specific impulses of this magnitude. For the chemically powered rockets, the weight of tanks, structure, and powerplant was assumed to be 10 percent of the vehicle gross weight. The hyperbolic velocities used were the same as those used in the nuclear-rocket calculations.

Deceleration into orbit about Mars. - It was decided to consider the possible use of a solid-propellant rocket to provide the retrothrust needed to attain an orbit about Mars from the vehicle's position in coast. Based on the best present operational solid propellants and case configurations, it was calculated that about one-half the weight in coast would be required for rocket propulsion. The value of specific impulse was assumed to be 300 seconds. This scheme would eliminate the need of afterheat cooling, because the nuclear powerplant would be jettisoned upon entering coast. A lighter propellant tank could be used because of the considerable lessening of meteoroid protection requirements. The tank and insulation would be discarded along with the nuclear powerplant.

Soft landing on Mars. - Another possible use of a solid-propellant rocket is to provide the deceleration required to effect a soft landing on the surface of Mars from the vehicle's position in orbit about Mars. It was calculated that an impulsive Δv of 2.9 miles per second (2.52 Int. naut. miles/sec) is required for this maneuver. Assuming use of a solid-propellant rocket with specific impulse of 300 seconds, it was estimated that about 20 percent of the weight leaving the orbit about Mars could be placed on the planet's surface. The nuclear powerplant, tank, insulation, structure, and Mars orbit vehicle guidance equipment would first be discarded.

This method of achieving a soft landing on Mars will be compared with all-nuclear propulsion. In the latter instance, only the Mars orbit vehicle guidance equipment is discarded before leaving the orbit around Mars. Again, the value of Δv required is 2.9 miles per second; but, because reactor power is used, specific impulse follows the schedule presented on page 6. With the use of reactor power, about 60 percent of the weight leaving the orbit about Mars could be placed on the surface. From the load delivered onto the surface, however, the weights of powerplant, tank, insulation, and structure must be subtracted to arrive at payload.

A third possibility is to use the atmospheric drag of Mars to provide the required deceleration from the orbit about Mars in making a soft landing, as suggested in reference 7. The payload compartment required would be in the form of a heavy, drag-type vehicle, such as described in reference 4.

RESULTS AND DISCUSSION

The effect of reactor power level cannot be isolated; therefore, it was necessary to study the influence of several other primary design factors. These primary factors include apoares altitude, coast time, hydrogen stagnation temperature in the nozzle, and vehicle weight leaving an orbit about Earth. The effects of these parameters on residual load are discussed with the aid of the figures. In most of the figures presented, a hydrogen stagnation temperature of 4500° F is assumed in the nozzle to provide an upper bound in the magnitudes of residual load. In addition, several secondary factors and comparisons with chemical rockets are also considered. These include the effect of firing a month before or after the optimum date, effect of the extent of meteoroid protection of the hydrogen tank, and comparisons with chemical vehicles including the use of a solid-propellant rocket to decelerate into orbit about Mars and the feasibility of making a soft landing on Mars.

Primary Factors

Apoares altitude. - The altitude at apoares need not be nearly so low as that at periares because obtaining information, such as photographing the planet, may best be accomplished from the periares. Accordingly, calculations were made to determine the weight of propellant required to achieve an elliptical orbit from a 200-day coast. The vehicle considered was assumed to have an empty weight of 33,000 pounds in the orbit about Mars and to be powered by a 1000-megawatt reactor heating hydrogen to 4500° F. The thrust-to-weight ratio of this vehicle is representative; therefore the trends should also be representative. The periares altitude remains fixed at 206 miles (179 Int. naut. miles). Apoares altitude is varied from the periares value to 30,000 miles (26,070 Int. naut. miles). The resulting plot, shown in figure 3, indicates that little propellant is to be saved by using apoares altitudes in excess of about 10,000 miles (8690 Int. naut. miles). Furthermore, about 70 percent more propellant is required to attain a circular orbit at a 206-mile altitude than an elliptic orbit with a 10,000-mile apoares altitude. Therefore, all further computations presented herein have been made for a 10,000-mile apoares altitude. This type of orbit is considered satisfactory for presently conceived scientific research. Incidentally, the period of this orbit is about 10 hours.

Coast time. - The coast time has a primary effect on propellant expenditure, and hence on residual load, by virtue of the hyperbolic velocities involved. These velocities have been discussed previously in connection with their presentation in figure 2.

The effect of coast time on hydrogen expenditure is shown in figure 4(a), in which the stagnation temperature of the hydrogen in the nozzle is assumed to be 4500° F. The ratio of propellant weight to vehicle weight leaving the orbit about Earth is plotted against coast time. Two values are shown for vehicle weights leaving the orbit about Earth. For 81,000-pound vehicles, reactor powers of 25 and 1000 megawatts are used; and for 33,000 pounds, a reactor power of 100 megawatts is presented. These curves all indicate that large savings in propellant can be realized at the expense of lengthening coast times up to about 230 days. Further increase in coast time yields small benefit. The slopes of the two curves for 81,000 pounds indicate that the rate of hydrogen savings with coast times rises with increasing reactor power.

This effect on hydrogen expenditure has been translated in terms of residual load plus powerplant weight in figures 4(b), (c), and (d). In these figures the ratio $W_{t+i+s}/W_{H_2,tot}$ has been assigned several discrete values in order to cover the expected range (0.16 to 0.28). Detailed design studies, such as reference 4, have shown that the value of this parameter decreases as vehicle weight rises. The increase in residual load plus powerplant weight with increasing coast time, as shown in figures 4(b), (c), and (d), is due to the decrease in total velocity change to accomplish the mission. The resulting decrease in total thrust requirement is mainly reflected in decrease in the weight of propellant required, as shown in figure 4(a).

It will be recalled that residual load includes vehicle guidance and control equipment, auxiliary power equipment, payload structure, payload container, and payload. Current estimates place the weight of vehicle guidance and control equipment, required to attain an orbit about Mars, at approximately 3000 pounds (1360 kg). About 2000 pounds (900 kg) is considered to be the minimum acceptable payload for this mission.

E-943

Therefore, residual load should be in excess of about 5000 pounds (2260 kg).

It is estimated that powerplant weight of vehicles considered herein will be at least 6000 pounds. A typical value for the ratio $W_{t+i+s}/W_{H_2,tot}$ is 0.24. Assuming these values for a 100-megawatt, 33,000-pound vehicle gives a residual load in orbit about Mars of 6300 pounds (2860 kg) after a 230-day coast (fig. 4(b)). For a 200-day trip the corresponding value of residual load is about 4500 pounds (2040 kg), which is considered marginal to be acceptable for this mission. Not even under the most optimistic conditions of figure 4(b) will short coast times (of about 150 days) be possible with a 33,000-pound vehicle. If powerplant weight exceeds about 7000 pounds, a 33,000-pound vehicle will probably be incapable of a Mars orbital mission.

Use of a larger vehicle (81,000 lb) is considered in figures 4(c) and (d). The stagnation temperature of the hydrogen in the nozzle remains at 4500° F. In figure 4(c), the reactor power is 25 megawatts. This figure is presented to indicate that a large vehicle is required if for any reason (such as temperature or stress limitations) the reactor must be restricted to very low power. The payload capacity of this large vehicle of low power is not a great deal better than that of the 100-megawatt, 33,000-pound vehicle. Figure 4(c) also shows that coast times of about 200 days are necessary for this large vehicle in order to yield acceptable payloads.

Better use of the larger vehicle is possible by increasing the reactor power, as shown by figure 4(d). This figure reveals that residual loads considerably greater than required for purposes such as picture-taking are possible for coast times of the order of 200 days. This fact points to two possible alternatives. Coast time can be decreased to about 145 days and still result in a satisfactory residual load. Another alternative is to make a soft landing on Mars, but this possibility will be dealt with subsequently.

Reactor power. - An indication of the effect of reactor power was evident in the previous discussion. The effect on residual load plus powerplant weight for a range of power from 10 to 1000 megawatts for both the 33,000- and 81,000-pound vehicles is presented in figure 5 for several values of the ratio $W_{t+i+s}/W_{H_2,tot}$. The hydrogen stagnation temperature in the nozzle is 4500° F, and a 200-day coast is assumed.

In figure 5(a), for 33,000-pound vehicles, the curves reach a maximum at about 500 megawatts and then drop off slightly because of the increasing afterheat coolant required. The knees of these curves, so to speak, occur at about 150 megawatts, beyond which little is to be gained in residual load. Figure 5(a) reveals that a 33,000-pound vehicle must be powered by at least 150 megawatts in order to deliver a residual load large enough to be considered acceptable. If $W_{t+i+s}/W_{H_2,tot}$ is 0.28

or greater, a 33,000-pound vehicle may not be capable of delivering an acceptable payload into orbit about Mars.

The curves for 81,000-pound vehicles (fig. 5(b)) rise with reactor power but have not reached a peak at 1000 megawatts. The knees of these curves occur at about 400 megawatts. At 150 megawatts for the 33,000-pound vehicle and 400 megawatts for 81,000 pounds, the initial acceleration is of the order of 1/4 g. Suitable reactor power for other vehicle weights will be discussed presently.

E-943

Hydrogen stagnation temperature in nozzle. - In a rocket engine, it is desirable to use as high a gas temperature in the nozzle as feasible in order to achieve high specific impulse. A primary constraint, however, is the stress in the reactor components at high temperature. Figure 6 presents the effect of hydrogen stagnation temperature in the nozzle on residual load for several design conditions. In this figure, $W_{t+i+s}/W_{H_2,tot}$ is 0.24 and powerplant weight is 6000 pounds. A comparison of residual loads over a range of reactor power for hydrogen stagnation temperatures of 4000° and 4500° F is presented in figure 6(a) for 81,000-pound vehicles. Over the range of power shown, the penalty in residual load due to the 500° F drop in propellant temperature is not excessive, nor does it vary greatly. At 400 megawatts the drop-off in residual load caused by heating the hydrogen to 4000° F instead of to 4500° F is about 1400 pounds (6.5 percent). The horizontal line shown in figure 6(a) pertains to chemical vehicles, which will be discussed in a subsequent subsection.

In figure 6(b) is shown essentially a linear relation between temperature and residual load for a given vehicle gross weight and reactor power. The range of hydrogen stagnation temperature presented is from 3500° to 4500° F. The fact that the slopes are not steep indicates that the gains to be had by raising the hydrogen temperature may possibly not be worth the additional problems in the reactor arising therefrom. Figure 6(b) is also provided to aid in estimating residual loads for temperatures intermediate between those selected for calculation. For the 33,000-pound vehicles the fact that residual load is less than 4000 pounds at 3500° F indicates that this temperature may be too low for a successful mission. A stagnation temperature of 4000° F appears to be a good compromise between rocket performance and severity of reactor materials problems.

Vehicle weight leaving orbit about Earth. - It was observed earlier that selection of reactor power level was dependent upon the vehicle gross weight leaving the orbit about Earth. Figure 7(a) presents the effect of this weight on residual load for vehicles powered by 25, 100, 500, and 1000 megawatts. Hydrogen stagnation temperature in the nozzle is 4500° F, and coast time is 200 days. The range of vehicle weights used is from 33,000 to 200,000 pounds. The solid curves, which are for nuclear vehicles, show essentially a linear relation between vehicle weight and residual load for a given value of reactor power. The dashed line, representing chemical vehicles, will be discussed later.

Consideration of any horizontal line in figure 7(a) shows the extent to which vehicle weight can be decreased by raising reactor power while maintaining a given value of residual load. For example, the same residual load that is obtainable from a 100-megawatt, 100,000-pound vehicle can be delivered by a 63,000-pound vehicle if reactor power is raised to 500 megawatts. The principal advantage of this action, however, is that the 37-percent saving in nuclear vehicle weight would be dwarfed by the much greater saving in weight of the booster used to place this vehicle in orbit about Earth. It was noted earlier that residual load should exceed 5000 pounds in order that an acceptable payload might remain after allowing for vehicle guidance and control equipment and other nonpayload items. With this limitation, figure 7(a) indicates that use of a nuclear-powered vehicle for this mission must await the development of chemical boosters with the capacity to place over 30,000 pounds in an orbit about Earth.

In figure 7(a) the residual loads are so high for the upper half of the 1000-megawatt curve that round trips might be feasible. Or, alternatively, the one-way trip time could be drastically reduced from the 200 days used in the figure.

Figure 7 may also prove useful in giving a rough approximation of residual load for vehicle gross weights other than those presented in figures 4 and 5.

A cross plot of figure 7(a) yields curves similar to those shown in figure 5. Such a set made for several values of vehicle weight is presented in figure 7(b) to indicate the approximate locations of the knees. It is again apparent that little gain in residual load is available by designing for higher values of reactor power than those corresponding to the knees. The dashed line in figure 7(b) is a locus of suitable reactor power. Residual load plus powerplant weight is used as the ordinate in figure 7(b) to avoid the restriction imposed by selection of a particular value of powerplant weight.

The locus of suitable reactor power is plotted against weight leaving the orbit about Earth in figure 7(c). The range in vehicle weights shown varies from 33,000 to 200,000 pounds, and reactor power varies from 150 to 1500 megawatts. Figure 7(c) indicates approximately the highest values of reactor power that can be advantageously used by vehicles in the weight range shown. It is apparent from figure 7(b), nevertheless, that a rather large deviation in power from the locus exists, so that considerable flexibility in the exact magnitude of power is available.

Figure 7(c) indicates, for example, that, for a 200,000-pound vehicle in orbit around the Earth, reactor power of the order of about 1500 megawatts would be a reasonable design choice. Reference to figure 7(b), however, shows that for this vehicle weight the reactor power can be halved with a reduction in the value of residual load plus powerplant weight of less than 6 percent. The corresponding decrease at 1000 megawatts is less than 2 percent, so that it might be said that 1000 megawatts is suitable for a 200,000-pound vehicle. This example clearly illustrates the flexibility available in choice of the magnitude of reactor power. This flexibility is greater at high vehicle weights. Furthermore, it can be concluded that, for Earth-orbital-launch vehicles up to 200,000 pounds in gross weight, there is practically no advantage in designing for reactor power in excess of about 1000 megawatts.

Secondary Factors

Firing a month before or after optimum date. - It is unlikely that ideal conditions will prevail to permit firing on the precise day for minimum sum of the hyperbolic velocities. Accordingly, the effect of providing a margin of plus or minus a month was studied. The results are presented in figure 8 for vehicle weights of both 33,000 and 81,000 pounds. Hydrogen stagnation temperature in the nozzle is 4500° F, and coast time is 200 days. The lower curves of the bands shown in figure 8 apply to firing 32 days early or 30 days late with respect to the date for minimum sum of the hyperbolic velocities. Therefore, the hyperbolic velocities used are greater than those shown in figure 2. Figure 8 reveals that, for the 33,000-pound vehicle, the feasibility of a Mars mission is dependent on firing close to the optimum date. For the 81,000-pound vehicle at 400 megawatts, the residual load would be reduced by as much as one-third because of 1 month's deviation in firing date. The corresponding decrease in payload would be about 40 percent (see ref. 4). It is likely that an actual vehicle would be designated for a point within the bands shown in figure 8. If it were designed for a point on the optimum curve and the optimum firing date could not be met, there would probably be no easy way to increase the tank size or increase the power. The alternative would be to modify the trajectory and increase coast time.

Meteoroid protection of hydrogen tanks. - The schedule of tank weight and probability of no hazardous hits by meteoroids taken from reference 3 applies to a vehicle of 30,600-pound weight leaving the orbit about Earth. The resulting residual loads are plotted in figure 9 against probability of no hazardous hits by meteoroids. In this figure the stagnation temperature of the hydrogen in the nozzle is 4000° F, reactor power is 150 megawatts, and coast time is 230 days. The levels of residual loads shown are based on an assumed powerplant weight of 6000 pounds. The curve in figure 9 is representative of other vehicle weights, reactor powers, and coast times considered in this report.

Any point on the curve of figure 9 gives the theoretical probability that all the meteoroids striking the tanks will not penetrate to a depth great enough to let the hydrogen escape. The circle shown on the curve at 57-percent probability designates that, if the inner tank is designed to withstand a pressure of 50 pounds per square inch absolute, it will be thick enough to provide the vehicle with a 57-percent chance of accomplishing its mission successfully. Similarly, the square on the curve indicates that the tank thickness required to withstand a pressure of 30 pounds per square inch absolute furnishes virtually no meteoroid protection.

Figure 9 shows that residual load drops off drastically at about 70-percent probability. To provide the greatest degree of meteoroid protection shown (92 percent) a penalty in residual load of 1100 pounds must be endured, as compared with the value obtained assuming the inner tank designed for 50 pounds per square inch absolute.

Comparisons with Chemical Rockets

Entire mission. - For chemical rockets, weights at Mars were calculated that correspond essentially to residual load of the nuclear-powered vehicles. Comparison is made for 200-day trips and with a specific impulse of 450 seconds, as discussed previously. The dashed line of figure 7(a) presents weights at Mars for chemical vehicles ranging in gross weight leaving an orbit about Earth from 33,000 to 200,000 pounds. This figure indicates that, except for the 25-megawatt curve, the nuclear vehicles shown surpass chemical vehicles over the entire range of vehicle weights presented. The steeper slopes of the curves for the nuclear vehicles indicate that, at vehicle weights below about 20,000 pounds, chemical vehicles would be superior. This is true mainly because the weight of the nuclear powerplant was assumed invariant with vehicle weight and hence is a higher percentage in the low vehicle-weight range. The minimum limitation of 5000 pounds for residual load, however, nullifies any implied advantage of chemical vehicles in the low vehicle-weight range. Furthermore, with this limitation, the dashed line of figure 7(a) indicates that the weight of chemical vehicles leaving an orbit around Earth for an orbit about Mars should be at least 50,000 pounds. But at this value of vehicle weight, a nuclear-powered vehicle has much greater potential payload capacity. These considerations indicate that a nuclear-powered vehicle has a decided advantage over a chemical vehicle for this mission.

In figure 10, which is primarily presented for another purpose (use of a solid-propellant rocket at Mars), a chemical vehicle is compared with nuclear vehicles for which reactor power varies. Vehicle weight is 33,000 pounds, and coast time is 200 days. The intersection of the horizontal line for chemical vehicles with the all-nuclear curve shows that nuclear vehicles have greater residual-load capability if reactor power exceeds about 50 megawatts. In an 81,000-pound vehicle (see fig. 6(a)), 50 megawatts is again the value of reactor power above which nuclear vehicles surpass chemical vehicles in payload performance.

Deceleration into orbit about Mars. - Because the residual loads provided by the 33,000-pound vehicle were low, it was decided to study the possible use of a solid-propellant rocket to enter the orbit about Mars. This was done in the hope that it might make even a low-power 33,000-pound vehicle feasible. The results are compared with those for all-nuclear propulsion in figure 10 for the 33,000-pound vehicle over a range of power after a 200-day coast. Hydrogen stagnation temperature in the nozzle chamber is 4500° F. This figure indicates that use of a solid-propellant rocket may yield gains in residual load at low reactor powers. These residual loads are at best marginal, however. Over the remainder of figure 10 there is no substantial change in residual loads between the two means of propulsion. It can therefore be concluded that the use of a solid-propellant rocket to attain an orbit about Mars from coast offers no advantage.

Soft landing on Mars. - An earlier discussion mentioned the possibility of making a soft landing on Mars by using the 81,000-pound vehicle. Such a mission might be desirable for the purpose of placing freight on Mars in support of a manned exploration that would utilize a larger vehicle. Two possible means of providing the deceleration are the use of a solid-propellant rocket and the use of the nuclear reactor.

A comparison of these two means of achieving a Mars soft landing is presented in figure 11 for a weight of 81,000 pounds leaving the orbit about Earth. Hydrogen stagnation temperature in the nozzle is 4500° F, the ratio $W_{t+i+s}/W_{H_2,tot}$ is 0.24, and powerplant weight is 6000 pounds. The weights shown in figure 11 for the solid rocket include the weight of the empty casing. For the all-nuclear vehicle, however, the weights consist only of payload and payload container.

The effect of varying reactor power is shown in figure 11(a) for a coast time of 200 days. This plot indicates that, with reactor power level above 400 megawatts, about 3000 pounds of freight can be placed on Mars' surface using a solid-propellant rocket. The all-nuclear vehicle has no Mars soft-landing capability for a 200-day trip. Even if coast time is increased to 260 days, the all-nuclear vehicle is marginal because it can place less than 2000 pounds on Mars' surface. This is shown in figure 11(b), in which reactor power is kept at 1000 megawatts while coast time varies. Use of a solid-propellant rocket in leaving the Mars satellite orbit will yield about 3850 pounds on the surface for a 230-day coast. These considerations reveal that, for a soft landing, a solid-propellant rocket used to leave the orbit about Mars has a greater payload capacity than the all-nuclear vehicle if the solid-propellant casing weighs no more than about one-half the total weight placed on the surface by this means.

In figure 11(a) a point encircled at a reactor power of 500 megawatts shows the effect of a month's deviation in firing date. Because the weight placed on the surface of Mars shown by this point is only 550 pounds (250 kg), it may be concluded that the firing date must be close to optimum for this mission.

If atmospheric drag is used to provide the required deceleration from the orbit about Mars, heavier weights can be placed on the surface. The heavy drag-type vehicle required to contain the payload might weigh about 5000 pounds. With this assumed value, figure 6(a) can be used to estimate the weight landed on the surface. If weights of 5000 pounds for the capsule and 3000 pounds for vehicle guidance and control equipment are subtracted from the residual load shown at 400 megawatts and 4000° F in this figure, a payload of about 12,000 pounds remains. Figure 8 shows that a one-month deviation in firing date would reduce the soft-landing payload 44 percent.

SUMMARY OF RESULTS AND CONCLUSION

The results of this parametric trajectory study on the possibility of using a nuclear-powered unmanned vehicle starting from an orbit about Earth to place a payload into an orbit about Mars having a 206-mile periares and a 10,000-mile apoares follow:

1. This use of nuclear vehicles must await development of chemical boosters capable of placing a weight of at least 30,000 pounds in orbit about Earth.

2. A 33,000-pound vehicle must be powered by about 150 megawatts to place an acceptable payload, of the order of 2000 pounds, into an orbit about Mars. Nuclear-powered vehicles have greater payload capacities for this mission than chemical vehicles for all values of reactor power greater than about 50 megawatts.

3. In a 33,000-pound vehicle, reactor power in excess of about 150 megawatts yields scarcely any payload increase in an orbit about Mars. The corresponding power for an 81,000-pound vehicle is about 400 megawatts, and for a 200,000-pound vehicle it is about 1000 megawatts.

4. A 4000° F hydrogen stagnation temperature in the nozzle appears to be a good compromise between rocket performance and severity of reactor materials problems. A stagnation temperature of 3500° F for a 33,000-pound vehicle may be too low to yield a successful Mars orbital mission.

5. To accomplish an acceptable Mars orbital mission, a 33,000-pound vehicle requires a coast time greater than 200 days. If reactor powerplant weight exceeds about 7000 pounds, this size vehicle is incapable of the cited Mars mission. Use of an 81,000-pound vehicle can reduce the required coast time to about 145 days.

6. Advancing or retarding the firing date by considerably less than one month from the optimum date would preclude the successful use of a 33,000-pound vehicle for a Mars orbital mission. For an 81,000-pound vehicle, a one-month deviation in firing date would decrease the payload in orbit about Mars about 40 percent.

7. There appears to be no payload advantage in discarding the nuclear powerplant before coast and using a solid-propellant rocket to enter the orbit about Mars.

8. It appears feasible to place freight on the surface of Mars using a 400-megawatt reactor in an 81,000-pound vehicle. If atmospheric drag is used to decelerate the payload capsule from its position in orbit about Mars, a weight of about 12,000 pounds can be placed on the surface.

9. A 200,000-pound vehicle powered by a 1000-megawatt reactor could be used either for round trips to Mars or to reduce drastically the coast time of one-way unmanned trips.

10. Meteoroid protection of the hydrogen tanks to the extent of providing a 92-percent probability of no hazardous hits decreases the payload in orbit about Mars by about 1100 pounds for a 30,600-pound vehicle.

From the results of this study it may be concluded that an acceptable payload (about 2000 lb) can be placed in orbit about Mars by an unmanned vehicle powered by a nuclear reactor of moderately low power (150 mw). The vehicle would be placed in an orbit about the Earth by a chemical booster of the Saturn class. A vehicle powered by a 400-megawatt reactor may place a weight of about 12,000 pounds on the surface of Mars with a soft landing if use is made of atmospheric drag at Mars.

Lewis Research Center
National Aeronautics and Space Administration
Cleveland, Ohio, August 23, 1960

E-943

APPENDIX A

SYMBOLS

F	thrust, lb
g	local value of gravitational constant, miles/sec^2
g_c	gravitational constant, miles/sec^2
I	specific impulse, sec
P	reactor power, watts
Q	heat, Btu
R_{in}	instantaneous radius of curvature, miles
r	radius measured from center of fixed coordinate system, miles
T_0	duration of reactor operation, days
t	time, sec
v	velocity, statute miles/sec (Int. naut. miles/sec)
W	weight, lb (kg)
y	residual load in orbit about Mars = vehicle guidance and control equipment + auxiliary power equipment + payload structure + payload container + payload, lb (kg)
β	central angle with reference to fixed coordinate system, radians
θ	angle between velocity vector and local horizontal, radians
μ	gravity force constant, $g \times (\text{planet radius})^2$, miles^3/sec^2
τ	duration from reactor startup to end of coast, days
ψ	angle between thrust and velocity vectors, radians
$\oplus$	Earth
♂	Mars

Subscripts:

a	beginning of phase
b	end of phase
H_2	hydrogen
h	hyperbolic
i	insulation
s	structure
t	tank
tot	total
1	power-on phase at Earth end of trip
2	coast
3	power-on phase at Mars end of trip
I	initial position of planet
II	final position of planet
$\oplus$	Earth
♂	Mars

E-943

APPENDIX B

TRAJECTORY ANALYSIS

The flight equations used for the orbital launch can be considerably simplified and still remain quite realistic, by neglecting the effects of planetary atmospheres on the mission. Stationary coordinates with the origin at the center of a uniform gravitational field were employed. For orbital launch the optimum thrust program closely coincides with "tangential" thrust (i.e., thrust alined with the velocity vector). Therefore, the assumption of tangential thrust seemed adequate for this report.

With these assumptions taken into account, the two equations that describe the balance of forces on the vehicle are

$$\frac{W}{g_c}\frac{dv}{dt} = F \cos \psi - \frac{W}{g_c} g \sin \theta \text{ (along path)} \tag{B1}$$

$$\frac{v^2}{R_{in}} = g \cos \theta - \frac{Fg_c}{W} \sin \psi \text{ (perpendicular to path)} \tag{B2}$$

The angle ψ is assumed zero when accelerating, and π when decelerating. Equation (B1) can be rearranged as follows:

$$\frac{dv}{dt} = \frac{Fg_c \cos \psi}{W} - g \sin \theta \tag{B3}$$

Assuming that $\psi = 0$, or π, equation (B2) then simplifies to

$$\frac{v^2}{R_{in}} = g \cos \theta \tag{B4}$$

The rate of rotation about the instantaneous center of curvature is related to the rate about the center of the planet (or fixed coordinate system) as follows:

$$\frac{v}{R_{in}} = \frac{d\beta}{dt} - \frac{d\theta}{dt} \tag{B5}$$

Equation (B5) may be rearranged as

$$R_{in} = \frac{v}{\frac{d\beta}{dt} - \frac{d\theta}{dt}} \tag{B6}$$

With the aid of the identity

$$\frac{d\beta}{dt} = \frac{v \cos \theta}{r} \tag{B7}$$

equation (B6) becomes

$$R_{in} = \frac{v}{\frac{v \cos \theta}{r} - \frac{d\theta}{dt}} \tag{B8}$$

Substituting equation (B8) into equation (B4) gives

$$\frac{v^2 \cos \theta}{r} - v \frac{d\theta}{dt} = g \cos \theta \tag{B9}$$

which rearranged yields the differential equation

$$\frac{d\theta}{dt} = \frac{-\left(g - \frac{v^2}{r}\right)\cos \theta}{v} \tag{B10}$$

Equations (B3) and (B10) are the two equations that are to be integrated stepwise with respect to time to give the velocity and position relative to the fixed coordinate system.

APPENDIX C

WEIGHT OF HYDROGEN FOR AFTERHEAT COOLING

It is intended to shut down the reactor once the hyperbolic velocity required for interplanetary coast has been attained. After shutdown, heat will continue to be released from the fission products because of the emission of beta particles and gamma rays. It will be necessary, therefore, to cool the reactor during coast by passing hydrogen through it.

The assumption will be made that the reactor continues to generate rated power until 30 seconds after shutdown. The heat thus produced during these 30 seconds is Q_1 Btu.

The rate of emission of beta and gamma energy is approximated by the following empirical expression, given in reference 8:

$$\frac{dQ_2}{d(\tau - T_0)} \approx 5.9\times10^{-3}\ P\left[(\tau - T_0)^{-0.2} - \tau^{-0.2}\right] \text{watts}$$

The energy Q_2 is calculated by integrating over the time interval between 30 seconds (expressed in terms of a day) and the time of coast $(\tau - T_0)$:

$$Q_2 = 0.4833\ P \int_{0.0003473}^{(\tau - T_0)} \left[(\tau - T_0)^{-0.2} - \tau^{-0.2}\right] d(\tau - T_0)\ \text{Btu}$$

$$Q_2 = 0.604\ P\left[(\tau - T_0)^{0.8} - \tau^{0.8} - (0.0003473)^{0.8} + (0.0003473 + T_0)^{0.8}\right] \text{Btu}$$

The total heat to be removed by the hydrogen is

$$Q_1 + Q_2$$

In the calculations it was assumed that the afterheat coolant left the reactor at 3960° R (2200° K). The rise in enthalpy of the hydrogen (from 260° R (144° K) inlet temperature) is therefore 14,000 Btu per pound. The weight of hydrogen required for afterheat cooling is thus

$$W_{H_2,2} = \frac{Q_1 + Q_2}{14,000}\ \text{lb}$$

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E-943

TABLE I. - ASSUMPTIONS AND CONSTANTS

[Linear dimensions are in statute miles.[a]]

Radius of Earth, miles	3,964
Gravity force constant at Earth, $\mu_{\oplus}$, miles^3/sec^2	95,854
Radius of Mars, miles	2,057
Gravity force constant at Mars, $\mu_{♂}$, miles^3/sec^2	10,252
Launching orbit about Earth, miles (circular)	352
Periares altitude at Mars, miles	206
Apoares altitude at Mars, miles	10,000
Planets' orbits	Noncircular and noncoplanar
Firing date	That which yields minimum sum of hyperbolic velocities (except fig. 8)
Temperature of H_2 entering reactor, $^{\circ}R$	[b]260
Condition of H_2 in nozzle	Equilibrium
Nozzle velocity correction factor	0.98
Nozzle expansion ratio	30
$\frac{W_{t+i+s}}{W_{H_2,tot}}$	0.24 (except figs. 4 and 5)
H_2 trapped in lines, tanks, etc., percent	5
Powerplant weight, lb	[c]6000 (except figs. 4(b), 4(c), 4(d), 5, 7(b), and 7(c))

[a]1 statute mile = 0.86896 Int. naut. mile.

[b]144° K.

[c]≈2720 kg.

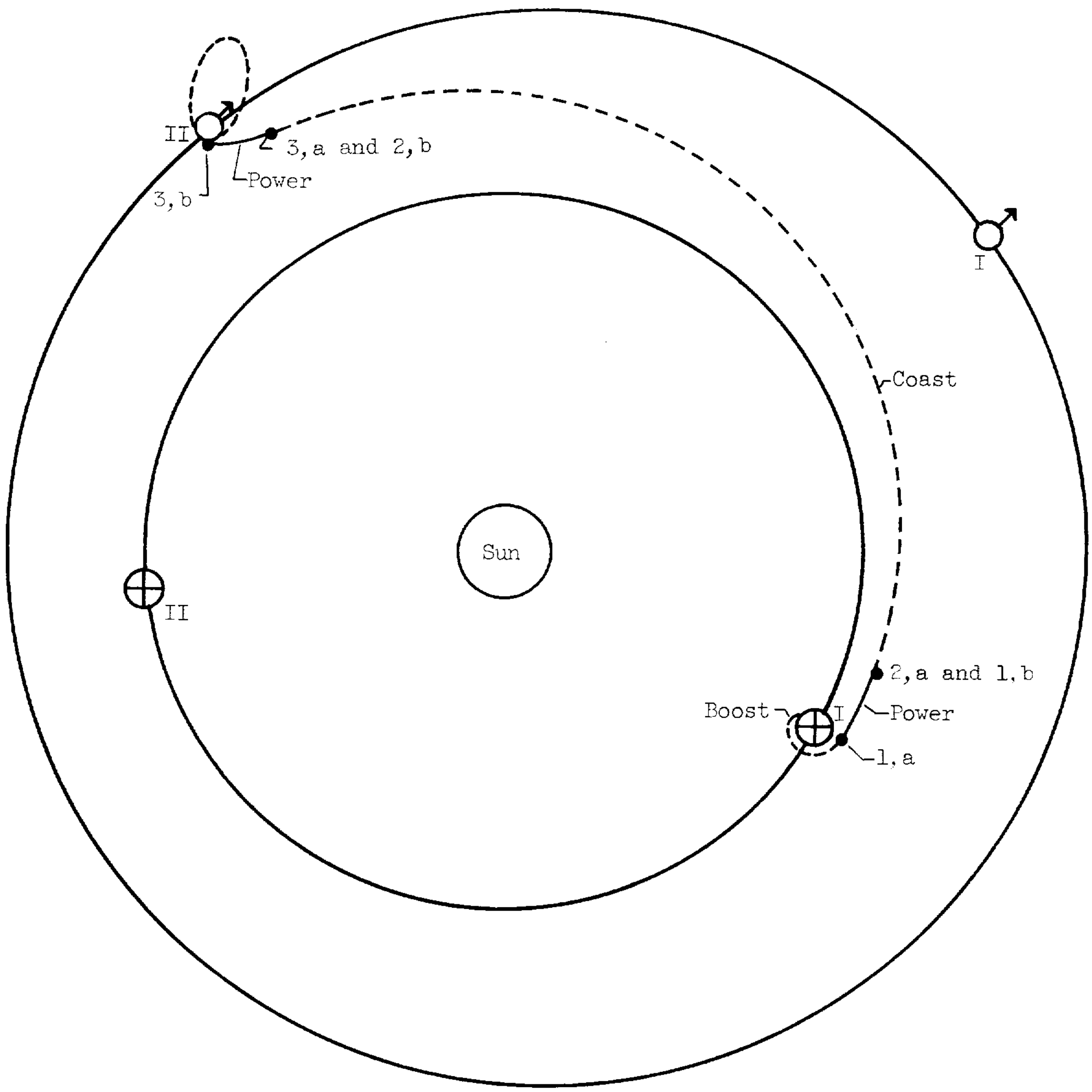


Figure 1. - Schematic diagram of trajectory in Sun-Earth-Mars system.

E-943

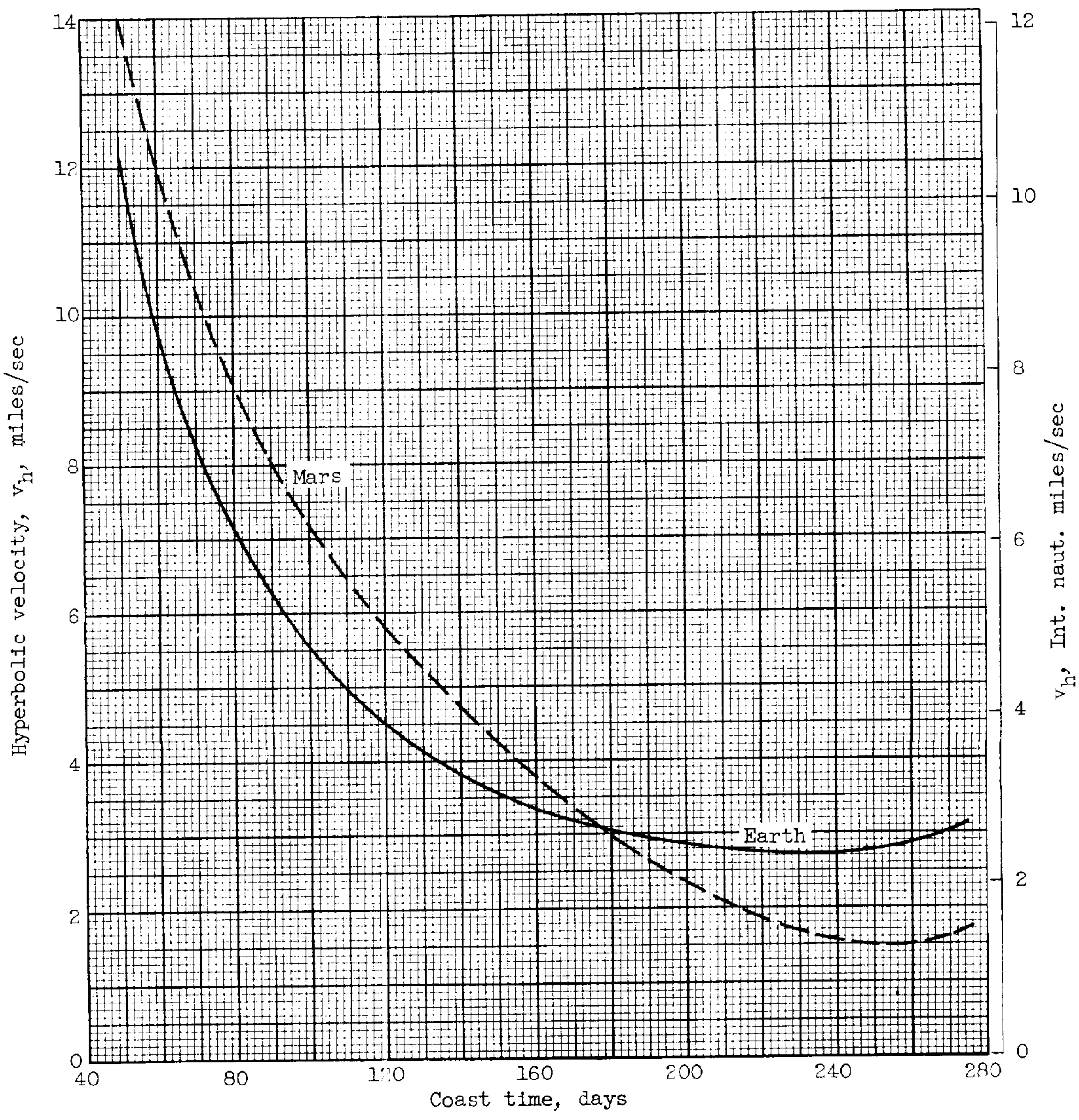


Figure 2. - Hyperbolic velocities at Earth and Mars to give minimum sum. (From unpublished NASA three-dimensional multiple two-body calculations.)

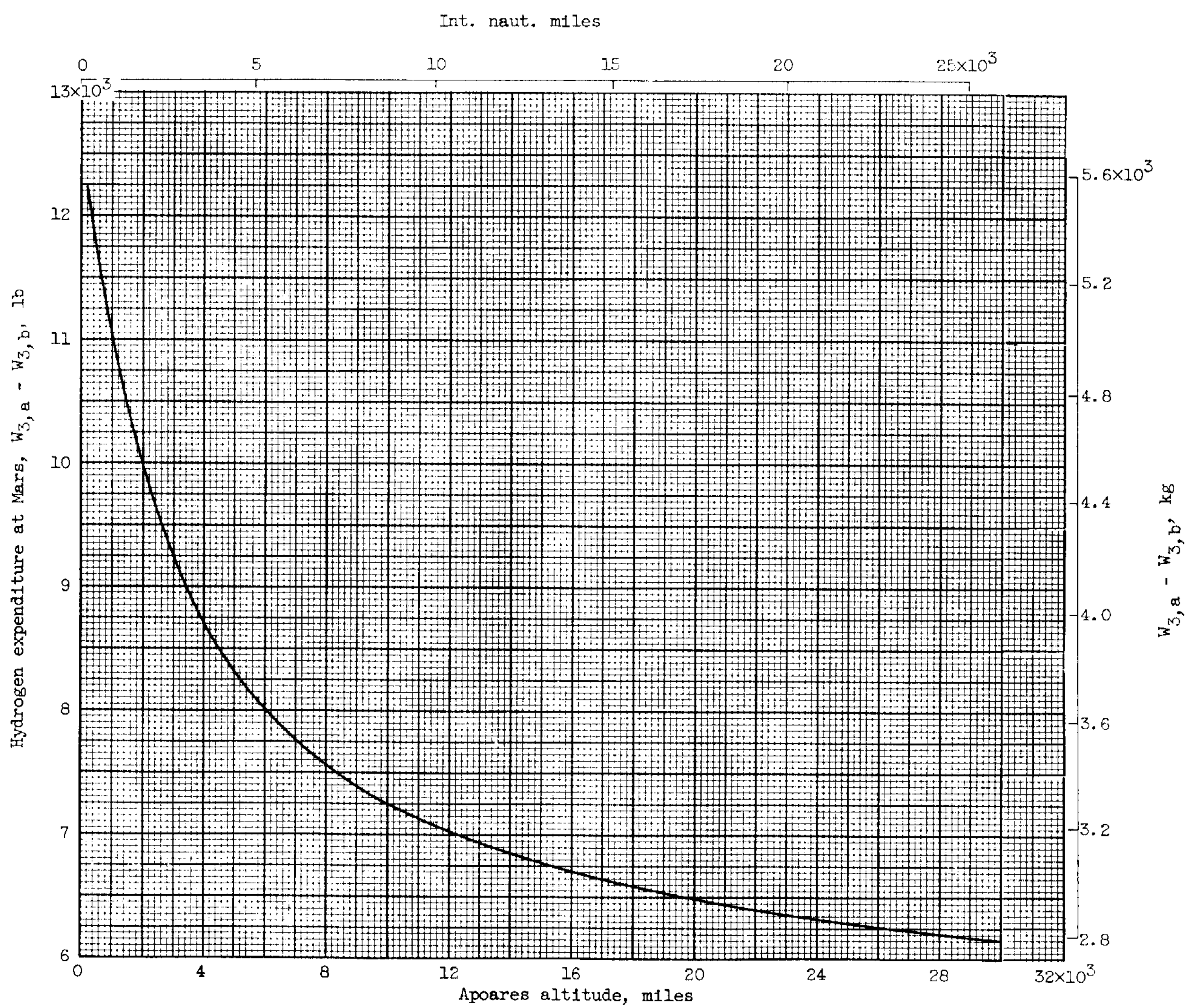
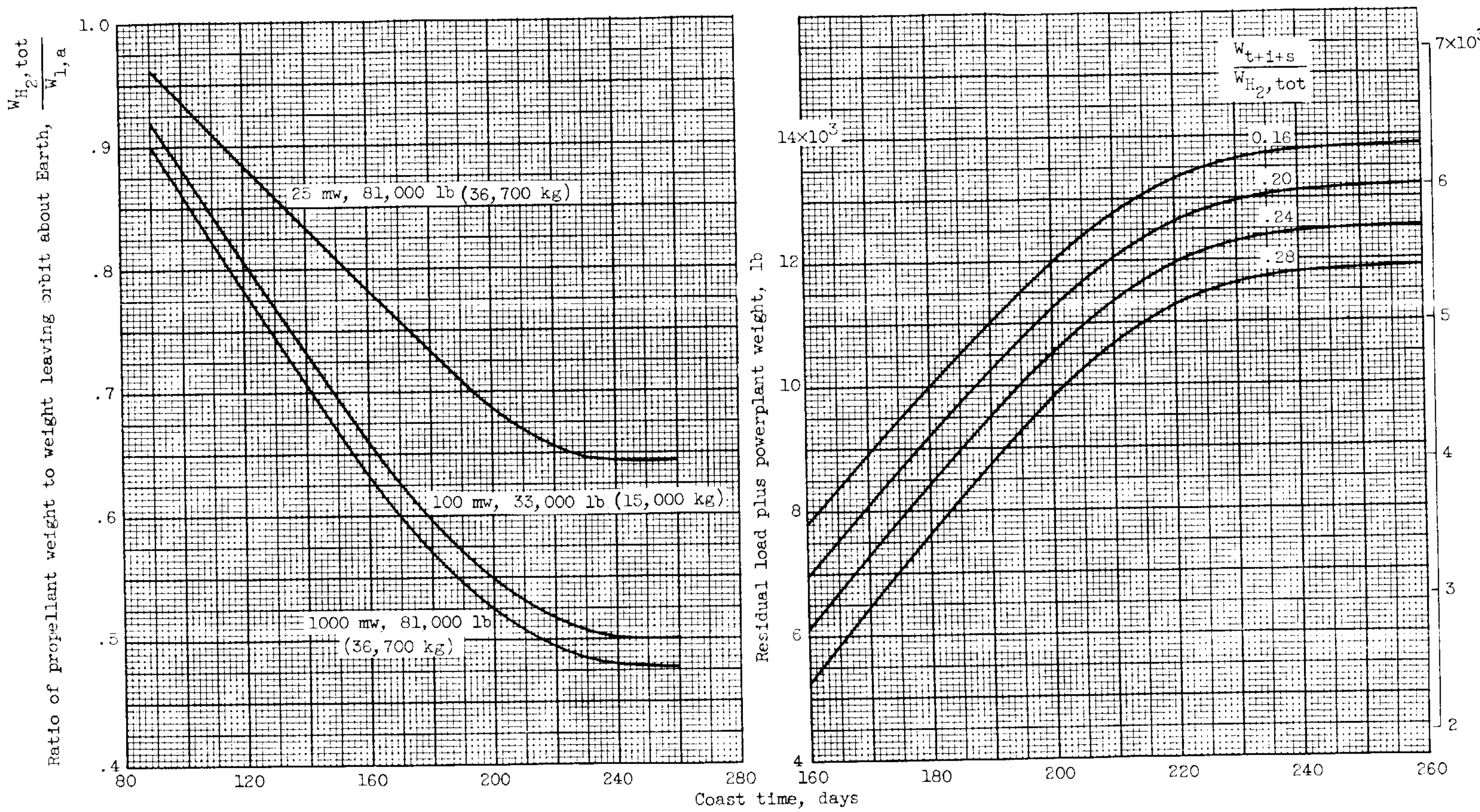


Figure 3. - Effect of apoares altitude on hydrogen expenditure to enter orbit about Mars. Reactor power, 1000 megawatts; hydrogen temperature, 4500° F (2500° C); coast time, 200 days; periares altitude, 206 miles (179 Int. naut. miles); empty weight $W_{3,b}$, 33,000 pounds (15,000 kg).

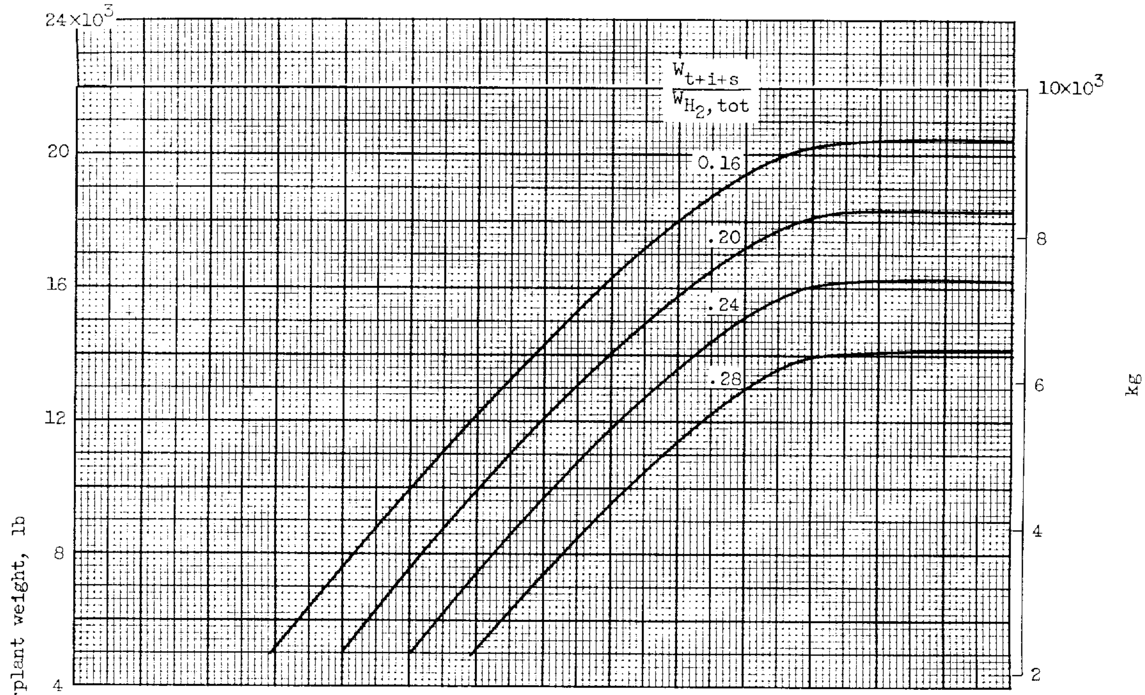


(a) Effect on hydrogen expenditure.

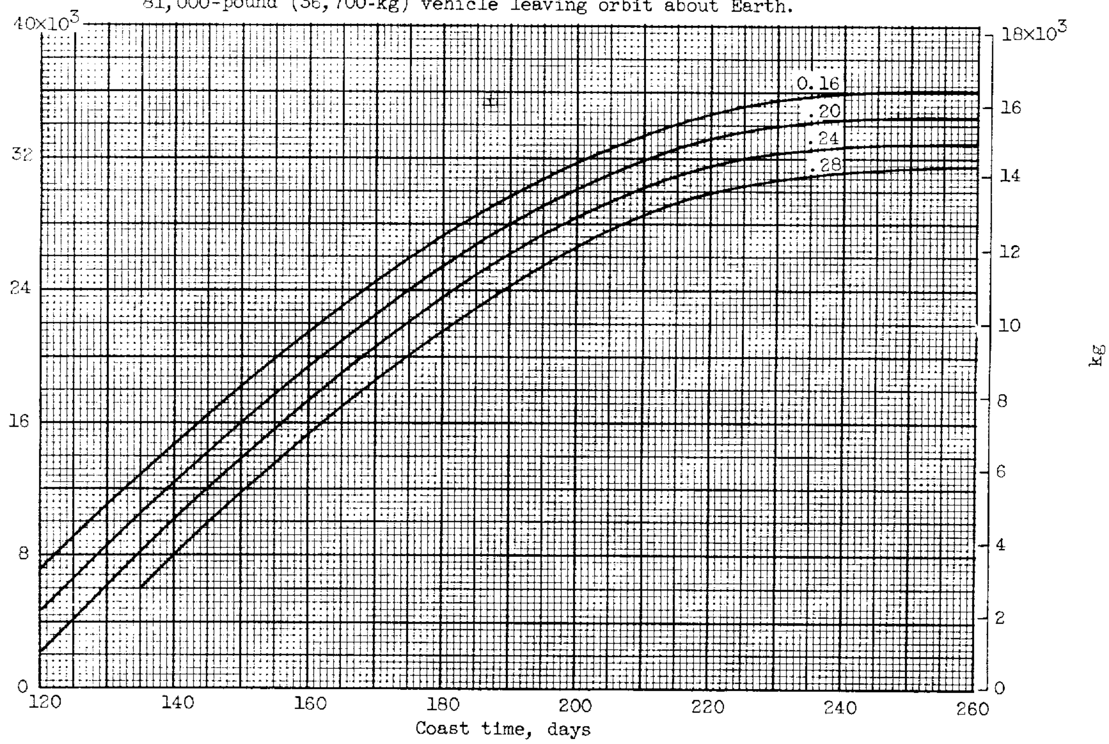
(b) Effect on residual load plus powerplant weight for 100-megawatt, 33,000-pound (15,000-kg) vehicle.

Figure 4. - Effect of coast time. Hydrogen temperature, 4500° F (2500° C).

E-943

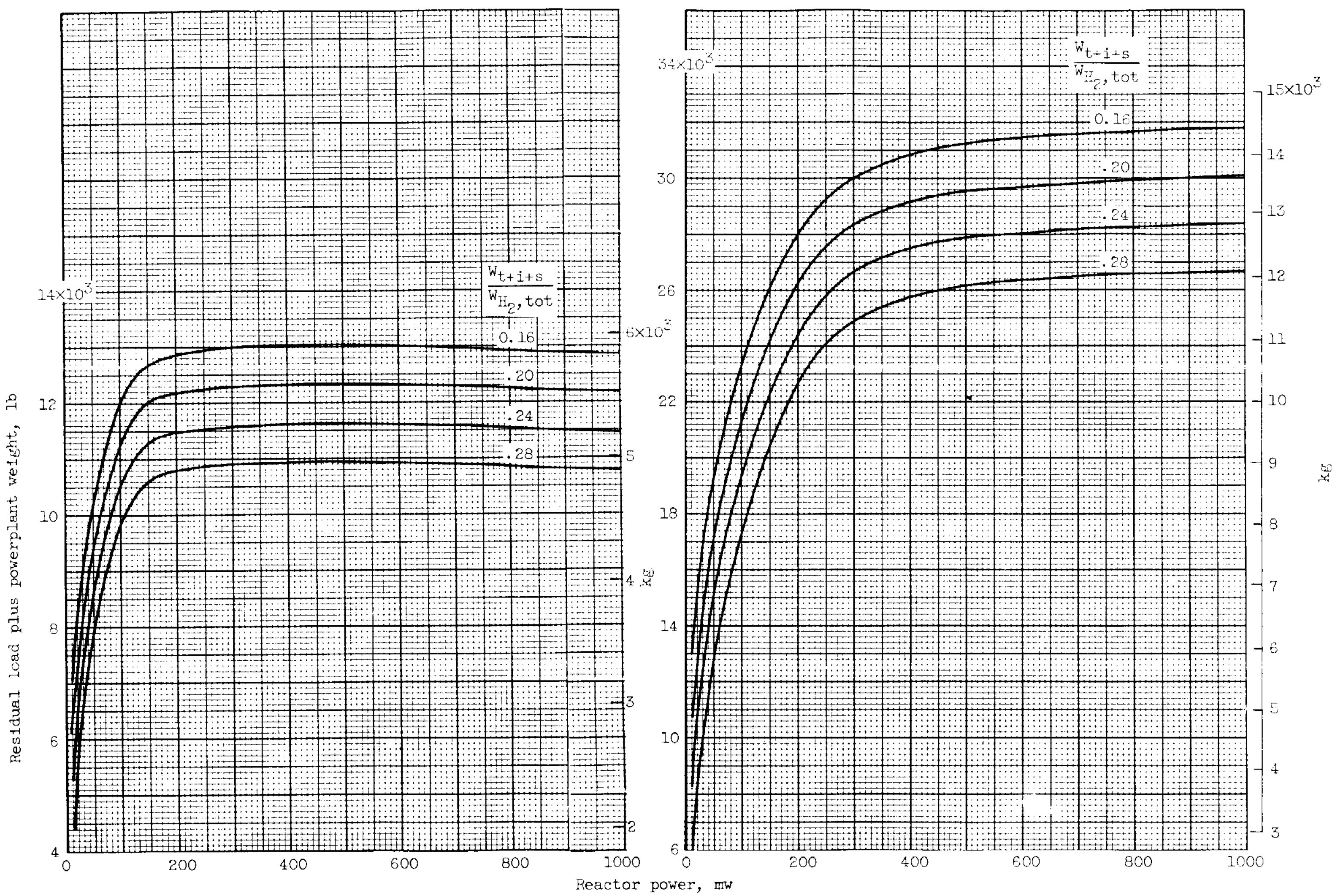


(c) Effect on residual load plus powerplant weight for 25-megawatt, 81,000-pound (36,700-kg) vehicle leaving orbit about Earth.



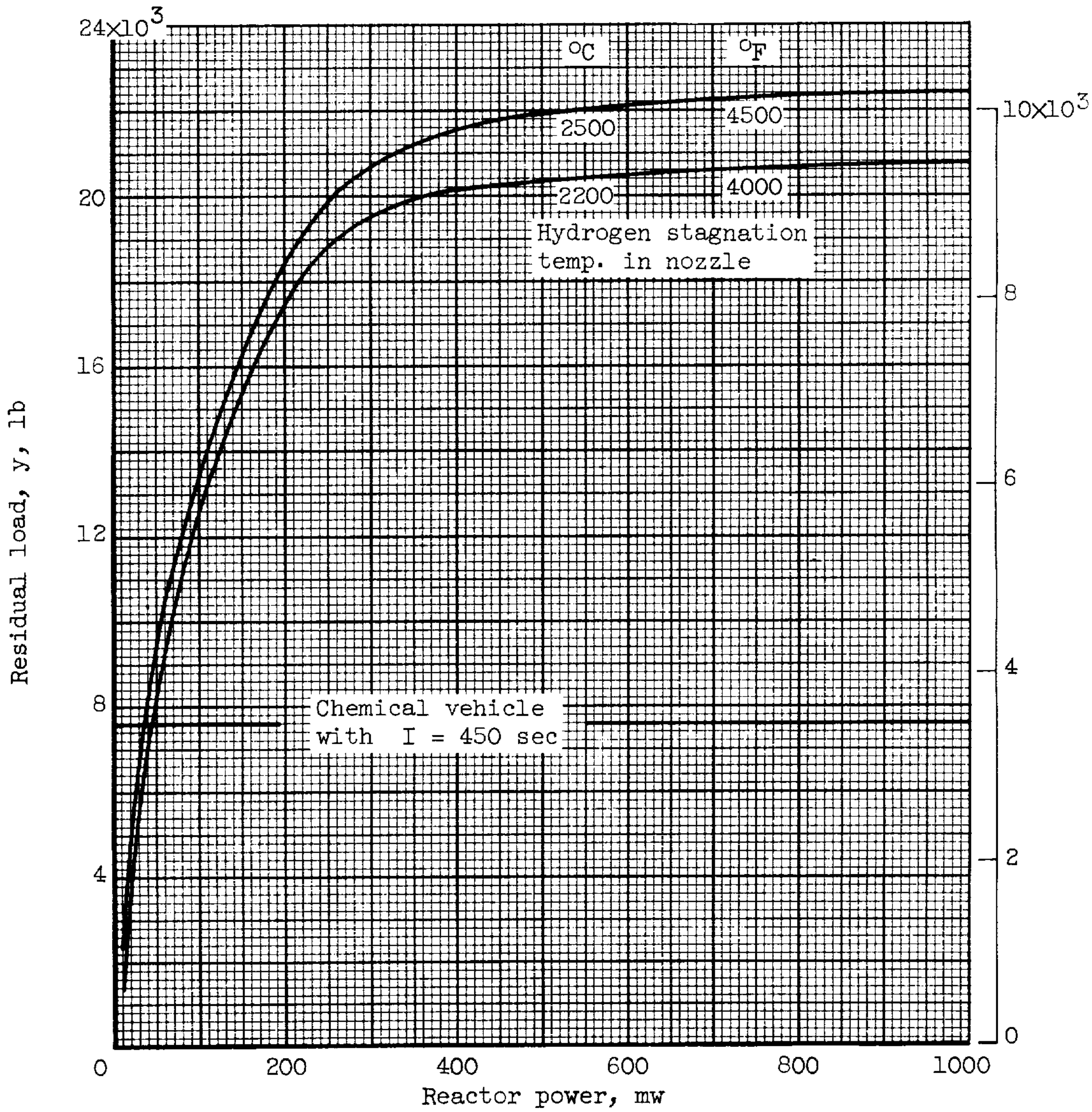
(d) Effect on residual load plus powerplant weight for 1000-megawatt, 81,000-pound (36,700-kg) vehicle.

Figure 4. - Concluded. Effect of coast time. Hydrogen temperature, 4500° F (2500° C).



(a) For 33,000-pound (15,000-kg) vehicle leaving orbit about Earth. (b) For 81,000-pound (36,700-kg) vehicle leaving orbit about Earth.

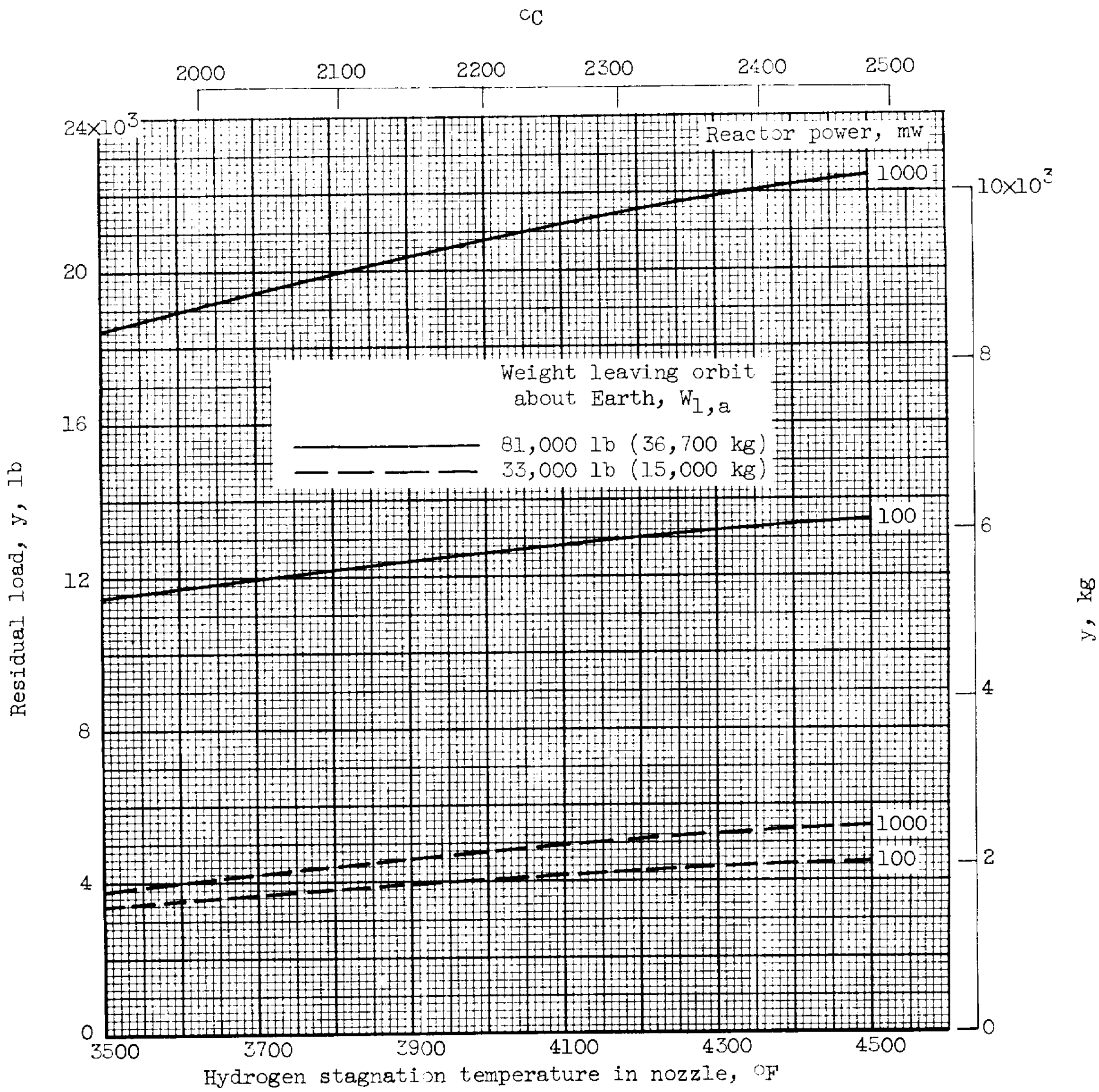
Figure 5. - Effect of reactor power. Hydrogen temperature, 4500° F (2500° C); coast time, 200 days.



(a) Variation with reactor power; 81,000-pound (36,700-kg) vehicle leaving orbit about Earth.

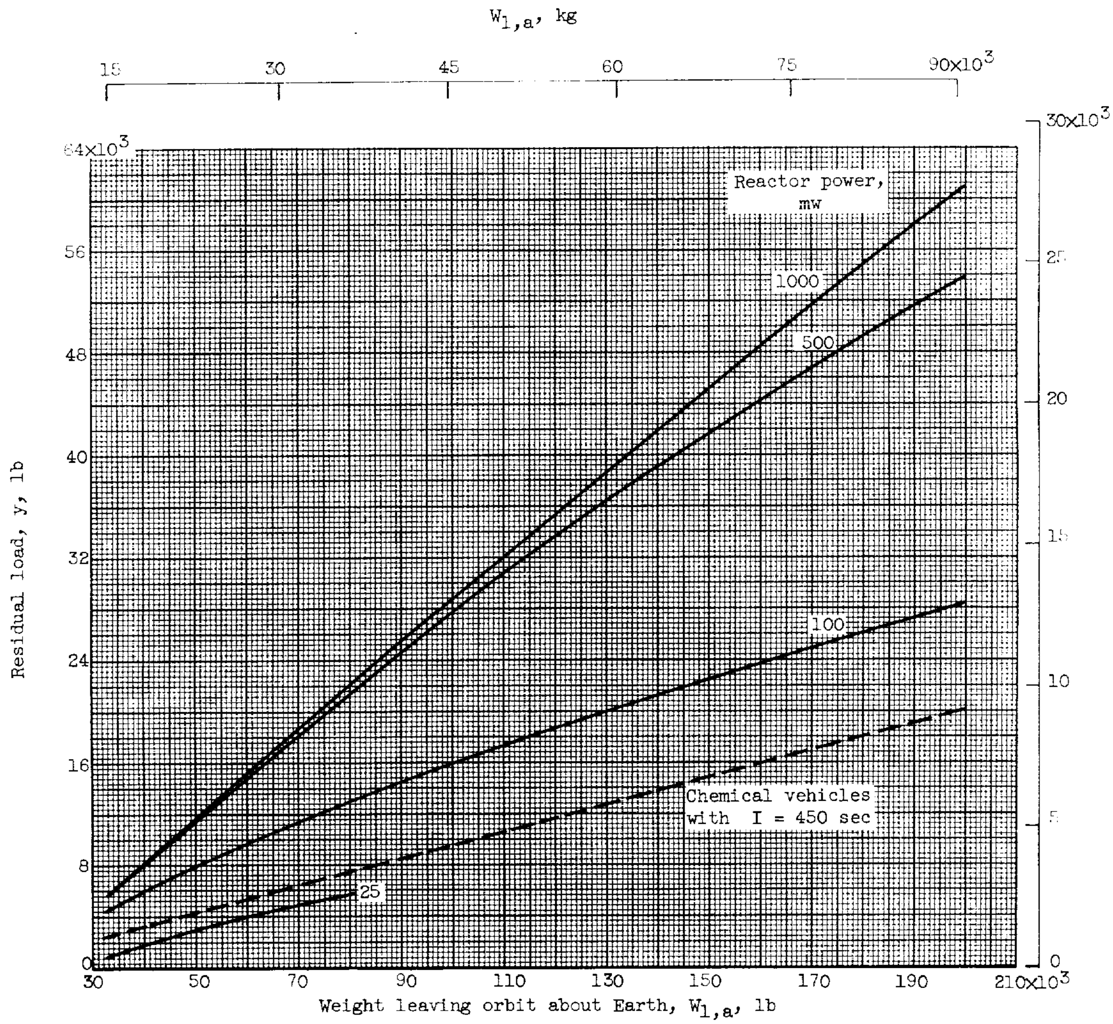
Figure 6. - Effect of nozzle stagnation temperature on residual load. Coast time, 200 days; $W_{t+i+s}/W_{H_2,tot}$, 0.24; powerplant weight, 6000 pounds (2720 kg).

E-943



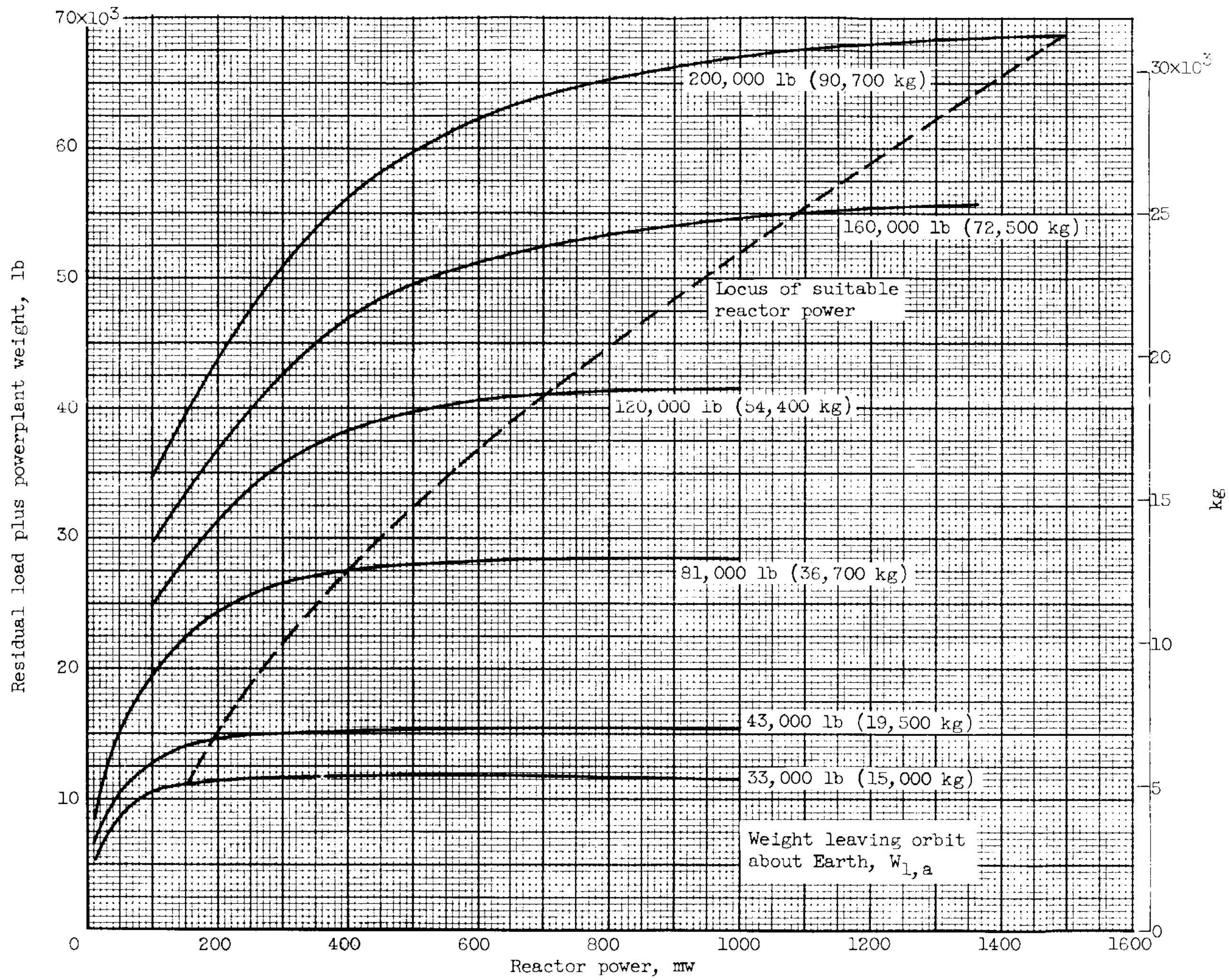
(b) Variation with weight leaving orbit about Earth.

Figure 6. - Concluded. Effect of nozzle stagnation temperature on residual load. Coast time, 200 days; $W_{t+i+s}/W_{H_2,tot}$, 0.24; powerplant weight, 6000 pounds (2720 kg).



(a) Effect on residual load. Powerplant weight, 6000 pounds (2720 kg).

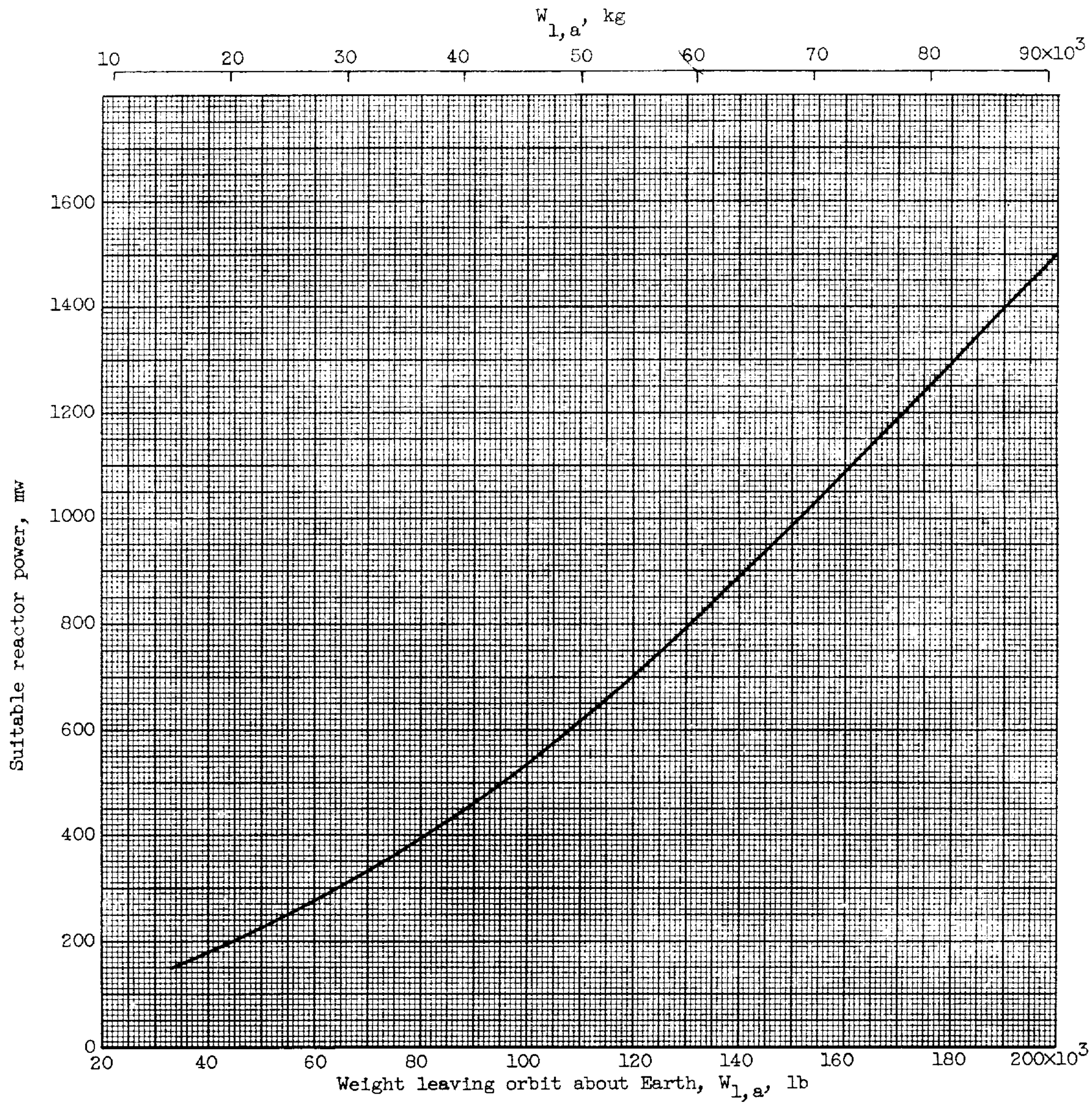
Figure 7. - Effect of weight leaving orbit about Earth. Hydrogen temperature, 4500° F (2500° C); coast time, 200 days; $W_{t+i+s}/W_{H_2,tot}$, 0.24.



(b) Effect on residual load plus powerplant weight (cross plot of fig. 7(a)).

Figure 7. - Continued. Effect of weight leaving orbit about Earth. Hydrogen temperature, 4500° F (2500° C); coast time, 200 days; $W_{t+i+s}/W_{H_2,tot}$, 0.24.

E-943



(c) Effect on suitable reactor power.

Figure 7. - Concluded. Effect of weight leaving orbit about Earth. Hydrogen temperature, 4500° F (2500° C); coast time, 200 days; $W_{t+i+s}/W_{H_2,tot}$, 0.24.

E-943

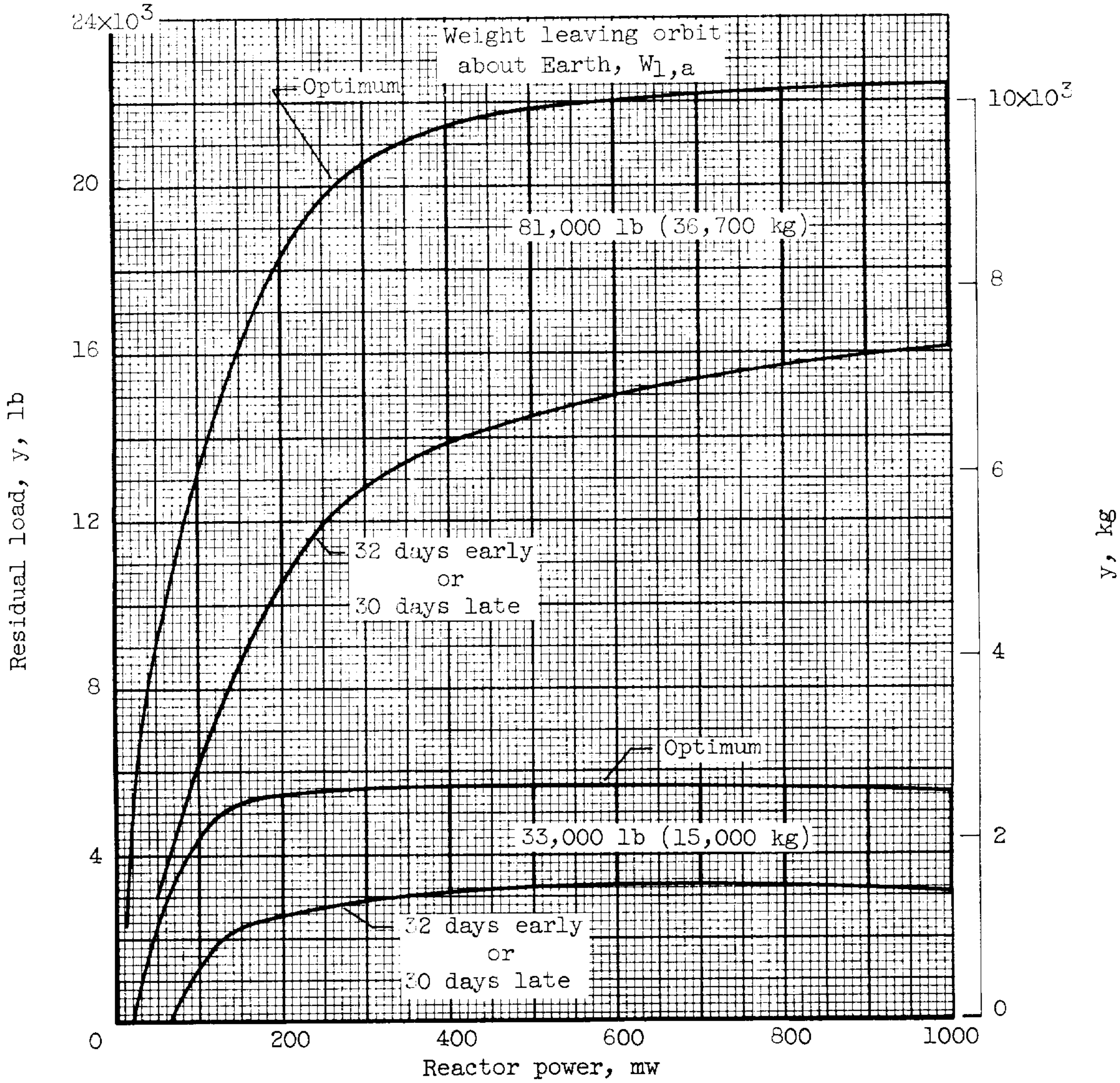


Figure 8. - Effect of firing before or after optimum date. Hydrogen temperature, 4500° F (2500° C); coast time, 200 days; $W_{t+i+s}/W_{H_2,tot}$, 0.24; powerplant weight, 6000 pounds (2720 kg).

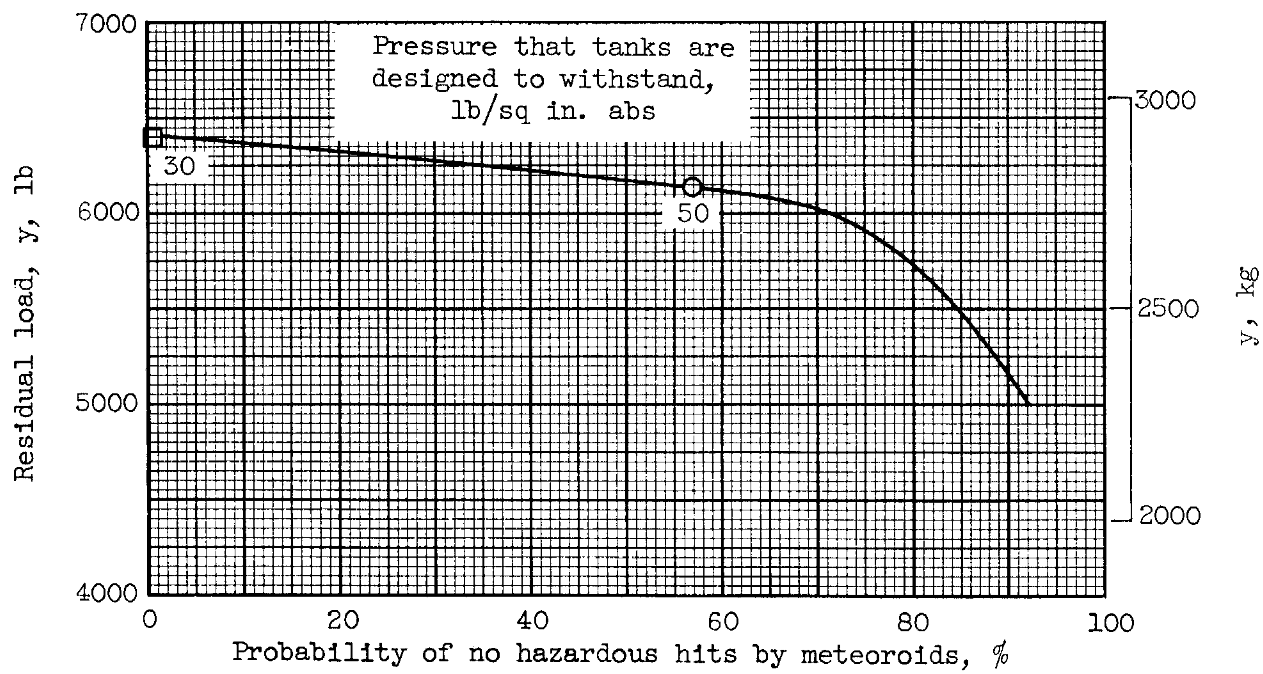


Figure 9. - Effect of extent of meteoroid protection of hydrogen tanks on residual load. Hydrogen temperature, 4000° F (2200° C); 30,600-pound (13,880-kg) vehicle leaving orbit about Earth; coast time, 230 days; reactor power, 150 megawatts; powerplant weight, 6000 pounds (2720 kg); W_{i+s}/W_t, 0.54.

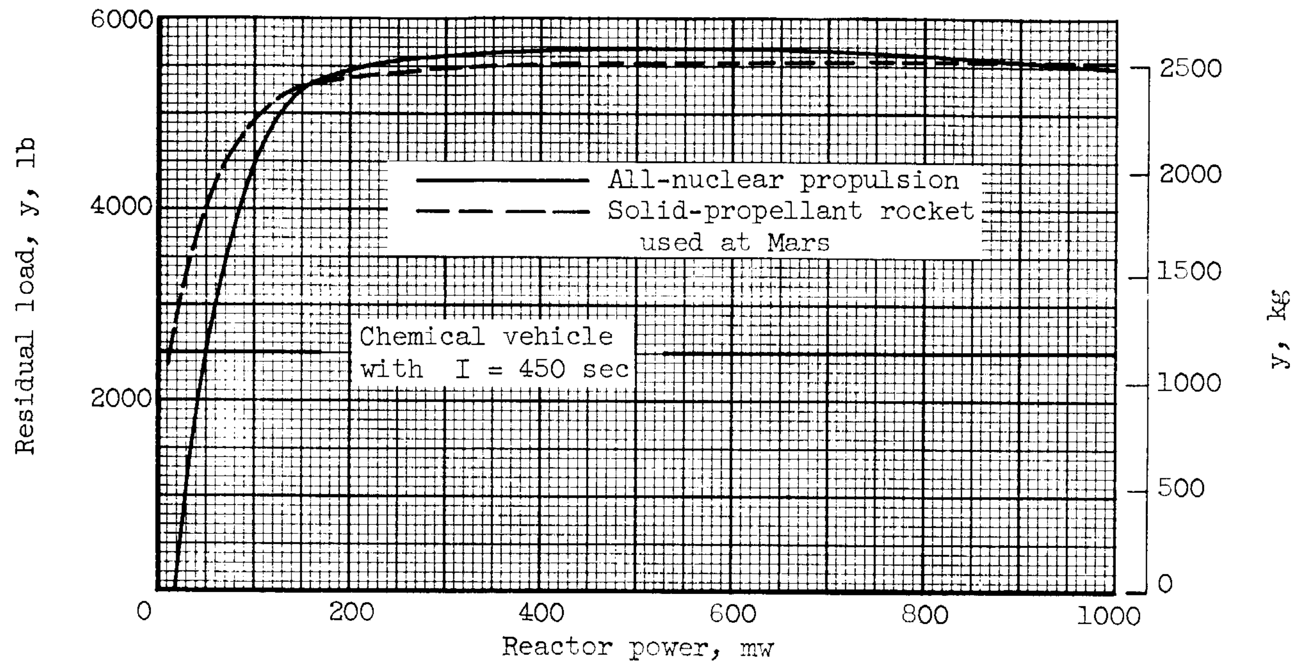
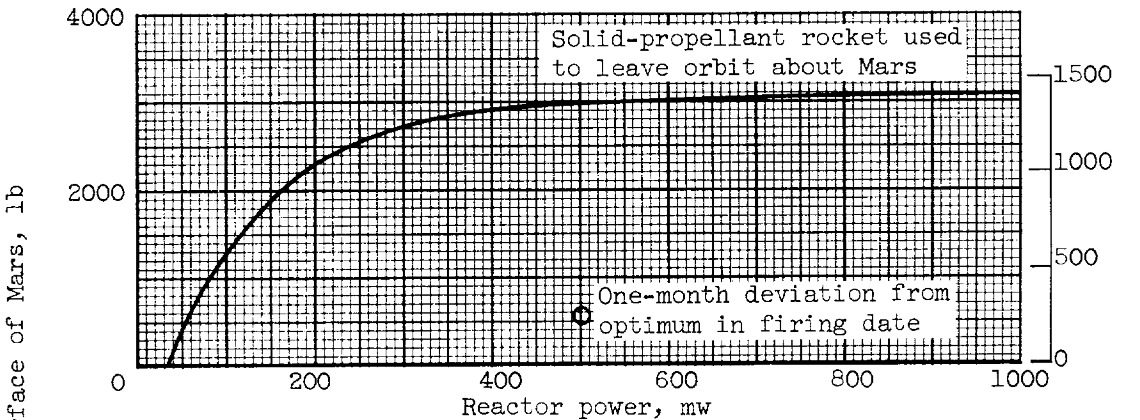
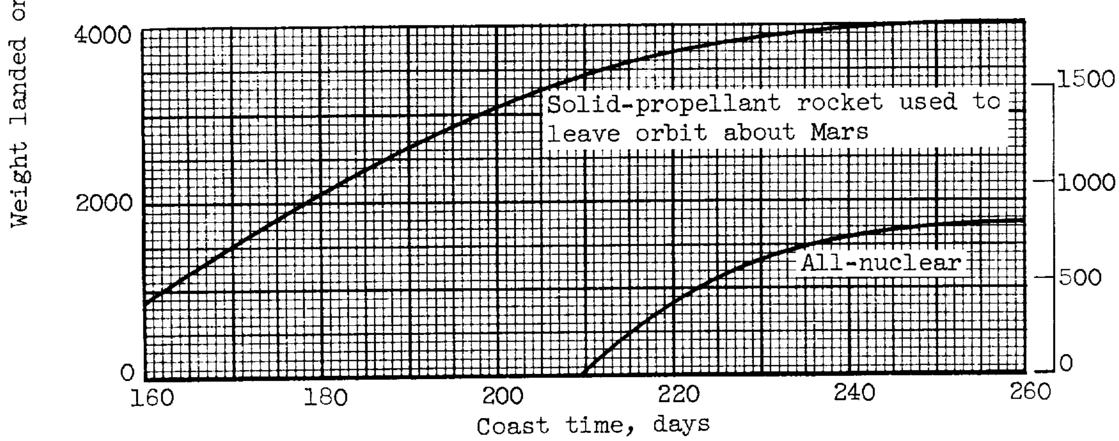


Figure 10. - Effect of using solid-propellant rocket to achieve orbit about Mars from coast. Hydrogen temperature, 4500° F (2500° C); coast time, 200 days; $\left(\frac{W_{t+i+s}}{W_{H_2,tot}}\right)_{\text{All nuclear}}$, 0.24; powerplant weight, 6000 pounds (2720 kg); 33,000-pound (15,000-kg) vehicle leaving orbit Earth.



(a) Effect of reactor power for 200-day coast.



(b) Effect of coast time for 1000-megawatt power.

Figure 11. - Soft landing on Mars. Hydrogen temperature, 4500° F (2500° C); 81,000-pound (36,700-kg) vehicle leaving orbit about Earth; $W_{t+i+s}/W_{H_2,tot}$, 0.24; powerplant weight, 6000 pounds (2720 kg).